

EPITHERMAL QUARTZ-ALUNITE AU DEPOSITS (MODEL 25e; Berger, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Central advanced argillic zone has iron-, copper-, and arsenic-rich sulfide and sulfosalt minerals with high acid-generating capacity; deposits consist of vuggy veins and breccias in highly acid-altered volcanic rocks with very low acid-consuming capacity. Central advanced-argillic zone is flanked by argillic and distal propylitic zones with some acid-buffering capacity, decreased copper and arsenic abundances, and increased zinc and lead abundances.

Examples

Summitville and Red Mountain Pass, Colo.; Goldfield, Nev.; Paradise Peak, Nev.; Julcani, Peru.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include porphyry copper (Model 17), porphyry gold-copper (Model 20c), and porphyry copper-molybdenum (Model 21a).

Potential environmental considerations

- (1) Dominant mining activity is in sulfide-mineral-rich, strongly altered volcanic rocks with negligible acid-buffering capacity.
- (2) Very high potential for the generation of acid-mine drainage (pH 1.5 to 3) that contains thousands of mg/l iron and aluminum; hundreds of mg/l copper and zinc (copper>zinc); hundreds of µg/l to tens of mg/l As, Co, Ni, Cr, U, Th, rare earth elements; tens to hundreds of µg/l beryllium; and anomalous abundances of bismuth, antimony, thallium, selenium, and (or) tellurium (Plumlee and others 1995a).
- (3) Unoxidized sulfide minerals can persist in clay-rich alteration zones to within 10 m of ground surface. Exposure of these sulfide minerals during mining can further enhance potential for acid-drainage generation.
- (4) In temperate or seasonally wet climates, soluble secondary iron, aluminum, and copper sulfate minerals dissolve during storm events and snowmelt, and lead to short term pulses of highly acidic, metal-bearing water from mine sites. The sulfate salts form by evaporation of acid mine water above the water table in open pits and underground mine workings during dry periods, even in wet climates.
- (5) Potential downstream environmental effects of acid drainage can be significant in magnitude and spatial extent, especially if surrounding terrane is composed primarily of volcanic rocks with low acid-buffering capacity. Dominant downstream signatures include water having low pH, and high iron, aluminum, manganese, copper, and zinc abundances.
- (6) Amalgamation-extraction of gold carried out during historic operations may be a residual source of mercury.
- (7) Smelter emissions at historic sites have elevated abundances of arsenic, copper, and zinc, and possibly other elements such as beryllium and tellurium.
- (8) Highly oxidized deposits and (or) deposits located in arid climates probably have lower potential for acid mine drainage and other environmental problems.
- (9) Cyanide heap leach solutions are composed predominantly of copper-cyanide complexes and thiocyanate.

Mitigation and remediation strategies for potential environmental concerns presented above are described in the section below entitled "Guidelines for mitigation and remediation."

Exploration geophysics

Resistivity studies can be used to help map features such as alteration zones. Potassium contained in alteration alunite may be identified by gamma ray spectrometry. Alteration mineral assemblages and stressed vegetation can also be identified using multispectral scanning remote sensing techniques such as AVIRIS.

References

Geology: Stoffregen (1987), Vikre (1989), Ashley (1990), John and others (1991), Deen and others (1994), and Gray and Coolbaugh (1994).
Environmental geology, geochemistry: Koyanagi and Panteleyev (1993), Gray and others (1994), Smith and others (1994), and Plumlee and others (1995a,b).

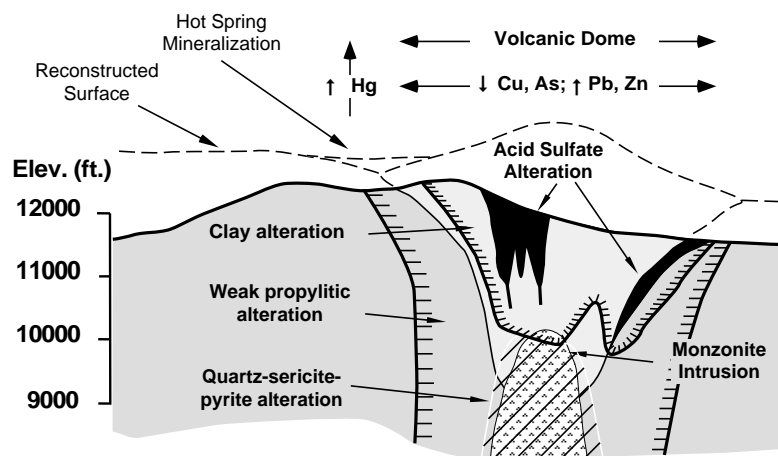


Figure 1. Simplified geologic cross section of an epithermal quartz-alunite Au deposit. Based on Summitville (Perkins and Neiman, 1982; Plumlee and others, 1995a) but modified to incorporate data from Julcani, Peru (Deen and others, 1994) and Paradise Peak, Nev., (John and 1991).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size is generally small (0.1 million tonnes) to intermediate (12 million tonnes).

Host rocks

These deposits are hosted by felsic volcanic rocks, generally intrusions or lava domes (fig. 1), that have low acid-buffering capacity. Most of these volcanic rocks are part of composite stratovolcano complexes. Some ore may be hosted in older sedimentary or crystalline rocks surrounding lava domes.

Surrounding geologic terrane

Surrounding geologic terrane is primarily volcanic but includes underlying sedimentary or crystalline rocks.

Wall-rock alteration

Wall-rock alteration reflects progressive wall-rock neutralization of highly acidic magmatic gas condensates; alteration predates ore formation. Alteration zoning shown on figures 1 and 2.

Intermediate-level advanced-argillic zone: Innermost vuggy silica, grading outward into quartz-alunite (\pm pyrophyllite), quartz-kaolinite, and montmorillonite-illite-smectite alteration zones. Pyrite present in all zones.

Phosphate minerals present primarily (?) in quartz-alunite zone.

Intermediate-level argillic zone: Montmorillonite-smectite-illite-clay minerals with pyrite.

Peripheral propylitic zone: Alteration of volcanic rocks to chlorite \pm epidote \pm pyrite \pm calcite.

Deep phyllic zone: Quartz-sericite-pyrite.

Nature of ore

In some deposits (e.g. Summitville) disseminated sulfide minerals are focused primarily in vuggy silica, quartz-alunite, and quartz-kaolinite zones; however, significant pyrite and other sulfide minerals also are present in clay altered zones, as disseminations within breccia, and in altered wall-rock veinlets. See figure 2 for typical sulfide mineral-sulfur content ranges for Summitville alteration zones. Although sulfide mineral-sulfur content is relatively low (<5 percent), the alteration process effectively removes nearly all of the rock's capacity to buffer acid.

Deposit trace element geochemistry

Deep: copper, \pm arsenic, \pm tungsten.

Intermediate inner: copper, arsenic, gold, \pm tellurium.

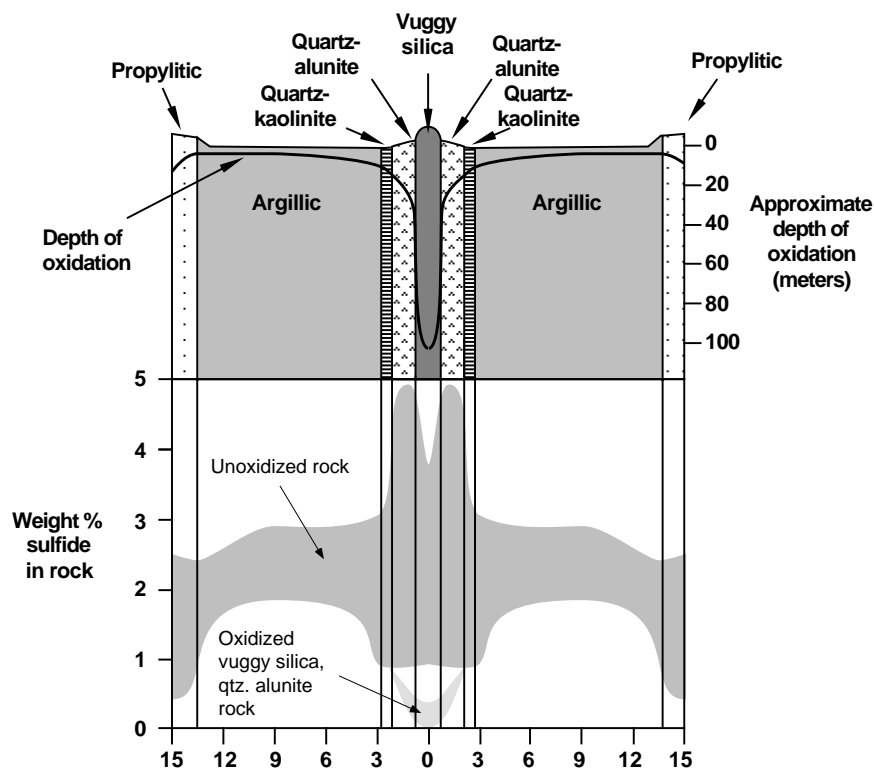
Intermediate peripheral: copper, lead, zinc.

Shallow, near surface: Mercury, arsenic, antimony, gold, thallium.

Ore at Paradise Peak contains elevated abundances of Au, Ag, Bi, Sb, Pb, Tl, Hg, S and Ba \pm Sn, Mo, Te, and Se.

In addition to iron sulfide (mostly marcasite), sulfate (barite) and native sulfur were abundant throughout the deposit.

Metal abundances in peripheral, argillically altered rock are essentially unchanged except that oxidized parts are



enriched in iron sulfide and unoxidized rocks contain gypsum and jarosite. Mineralized rock from the deepest part of this system tended to have elevated abundances of arsenic and copper but not as elevated as those characteristic of Goldfield, Nev. or Summitville, Colo.

Ore and gangue mineralogy and zonation

Minerals listed in decreasing order of abundance. Potentially acid-generating minerals underlined. In epithermal quartz-alunite gold deposits, ore deposition usually postdates development of argillic alteration.

Deep: Pyrite, chalcopyrite, tennantite, \pm wolframite-heubnerite (Julcani)

Advanced argillic, argillic alteration zones: Pyrite, enargite, covellite, chalcocite, chalcopyrite, native sulfur, marcasite, native gold, barite. Late barite, sphalerite, galena, \pm siderite (Julcani), \pm botryoidal pyrite.

Peripheral propylitic zone: Sphalerite, galena, \pm siderite, barite, \pm botryoidal pyrite

Shallow, near surface: Silica sinter, cinnabar, native mercury?, native gold, pyrite, marcasite, realgar, orpiment.

Mineral characteristics

Textures: Sulfide minerals form fine- to medium-grained (<5 mm), euhedral crystals and masses of very fine-grained, interlocking crystals. Some coarse-grained (as much as 4-5 cm) euhedral sulfide minerals also are present. Late-stage botryoidal pyrite and siderite are present in some deposits.

Trace element contents: Arsenic and antimony may be present in main-stage pyrite and (or) marcasite; late botryoidal pyrite, where present, is typically strongly enriched in arsenic, antimony, and other trace elements. Abundant stibnite-bismuthinite is the principal mineralogic site for antimony and bismuth in the Paradise Peak deposit.

General rates of weathering: Botryoidal, high trace elements > massive, fine >> coarse euhedral, low trace elements.

Secondary mineralogy

Readily soluble minerals underlined

Supergene minerals: Scorodite, goethite, limonite, K- and Na-jarosite, phosphate minerals, and plumbojarosite.

Minerals formed by recent weathering: Jarosite (likely hydronium-enriched), chalcantite, brochantite, melanterite, alunogen, halotrichite, and phosphate minerals?. These minerals form by evaporation of acid water during dry periods, and then redissolve during wet periods. These minerals can also form by evaporation in overbank stream sediment downstream from mine sites.

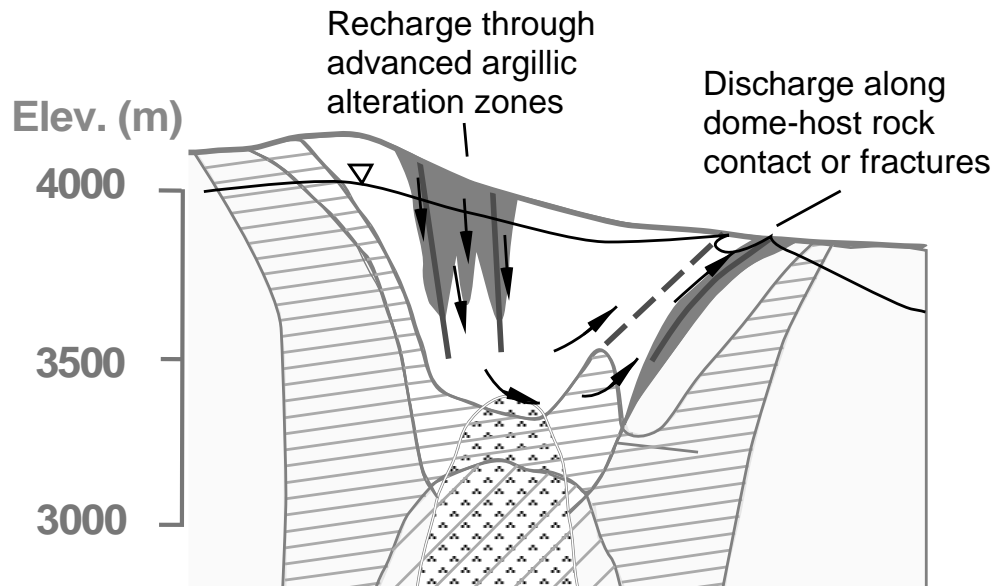


Figure 3. Inferred pre-mining hydrology at Summitville. Triangle marks position of water table.

Topography, physiography

Volcanic domes generally form topographic highs. Vuggy silica zones are resistant to weathering, and form prominent knobs and pinnacles. Because vuggy silica zones are highly resistant to weathering, physical erosion immediately surrounding clay alteration zones is minimal.

Hydrology

Pre-mining oxidation surfaces can help identify zones of high permeability within deposits. Ferricrete deposits mark pre-mining ground water discharge points. Vuggy silica alteration zones have the highest primary permeability and therefore focus ground water flow; most are oxidized to deep levels (100 meters) by pre-mining ground water. Clay alteration zones have the lowest permeability and therefore inhibit ground water flow; most are oxidized to only shallow levels (several meters to several tens of meters) by pre-mining ground water. Post-mineralization fractures can serve as conduits for ground water flow. Rock contacts between volcanic domes and surrounding rocks can be significant conduits for ground water flow and can also strongly influence distribution of alteration assemblages. In the vicinity of these deposits, the water table generally conforms to topography; the highest elevations are coincident with volcanic domes. At Summitville (fig. 3), ground water recharge is probably along vuggy silica zones. Ground water discharge prior to underground mining (marked by extensive ferricrete deposits) was primarily along contact between volcanic dome and host rocks, and at scarce locations where other fractures intersected the topographic surface of the volcanic dome. In the area around the Paradise Peak deposits, the water table is locally perched, which resulted in the presence of large blocks of unoxidized rock at shallow depths.

Mining and milling methods

Historic: Underground mine workings followed vuggy silica alteration zones in most cases. Ore was processed using stamp mills and mercury amalgamation or cyanide vat leach.

Modern: Modern operations principally involve open-pit mining of vuggy silica and surrounding clay alteration zones but include some underground mining. Ore is processed primarily using cyanide heap leach techniques.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data (figs. 4 and 5): Summitville and Red Mountain Pass, Colo. (Plumlee and others, 1993; Plumlee and others 1995a,b). Mine water draining ore hosted by advanced argillic altered rocks is highly acidic and contains high to extreme dissolved metal abundances, including hundreds to several thousands of mg/l iron, aluminum, and manganese; hundreds of mg/l zinc and copper; and hundreds of µg/l to several tens of mg/l As, Co, Ni, U, Th, Be, and REE. Water draining these deposits has elevated arsenic abundances; concentrations of uranium relative to zinc are unusual relative to those associated with many other deposit types. Preliminary data indicate that tellurium, mercury, and tungsten, though potentially enriched in advanced argillic ore, do not appear to be enriched in mine-

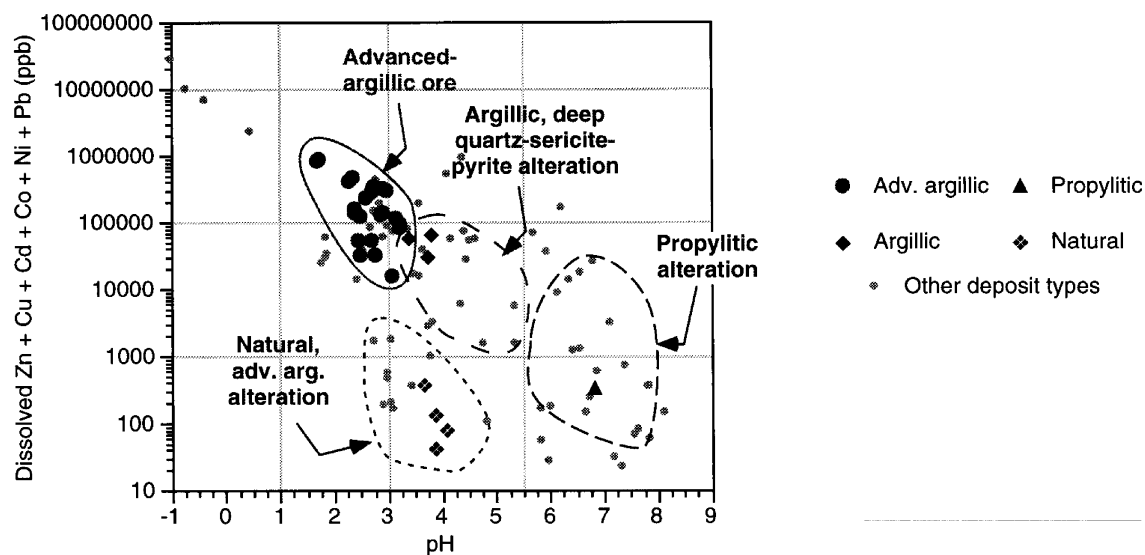


Figure 4. Plot of pH versus the sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining epithermal quartz-alunite Au deposits. Lines show inferred likely ranges of metal content and pH for specific alteration zones. Samples are water draining adits and waste dumps, rain and snowmelt puddles, and seeps. Data from Koyanagi and Panteleyev (1993) and Plumlee and others (1995b).

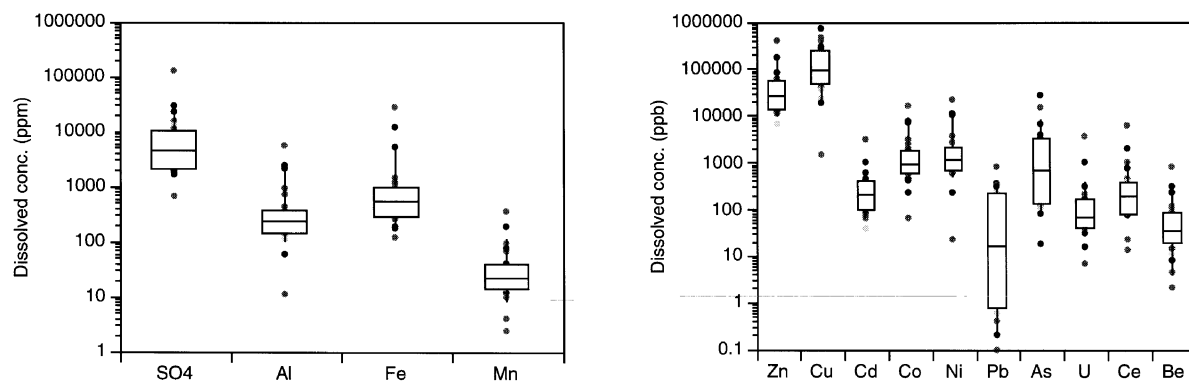


Figure 5. Box plots showing ranges of selected dissolved constituents in mine water draining ore hosted by advanced argillic alteration zones of epithermal quartz-alunite Au deposits. For each constituent, the box encloses samples falling between the 25th and 75th percentiles, the line shows the range between the 10th and 90th percentiles, and the dots show actual concentrations for samples falling outside the 25th and 75th percentiles.

drainage water. Limited data indicate that mine water draining argillic alteration zones has slightly higher pH and lower metal content.

Mine water draining shallow hot spring ore: No data available. The best currently available data are for water draining advanced-argillic, native sulfur-rich parts of a hot spring sulfur deposit (Leviathan, Calif.), which is acidic (pH 2-3) and has relatively low base metal contents but elevated abundances of arsenic, antimony, and thallium (Ball and Nordstrom, 1989).

Natural-drainage data: Limited data for a relatively wet climate with high dilution rates (British Columbia) suggest low acidity (pH between 2 and 3) and elevated dissolved metal abundances, including hundreds of mg/l iron and aluminum; abundances of copper and zinc, tens to hundreds of $\mu\text{g/l}$, are lower than those measured in mine drainages.

Potentially economically recoverable elements: High copper abundances in drainage water could be economically extracted.

Metal mobility from solid mine wastes

Metals and acid are readily liberated from sulfide-mineral-bearing mine wastes due to oxidation of sulfide minerals, mainly pyrite. During dry periods, secondary soluble salts form by evaporation. During wet periods, the soluble

salts are rapidly dissolved. These salts can be present as coatings on rock material. Metal and acid are probably not liberated in significant amounts from mine wastes associated with deposits oxidized extensively prior to mining. Storm water samples: The pH and metal contents of water in rain and snowmelt puddles, which contain dissolved soluble salts, is generally similar to that of water draining adits and waste dumps (Plumlee and others, 1995b). Water-rock leaching: The results of a few leaching experiments with advanced argillic waste rock material from Summitville (50 g sample in 1 liter of distilled water, Plumlee and others, 1995b) show that metal concentrations and pH values of leach water rapidly (within tens of minutes) approach those of water draining adits and mine dumps.

Soil, sediment signatures prior to mining

No data currently available.

Potential environmental concerns associated with mineral processing

Mercury amalgamation of ore during historic mining may provide a source of mercury contamination not directly attributable to epithermal quartz-alunite gold deposits.

Cyanide geochemistry: Heap leach and other cyanide processing solutions are likely to include copper-cyanide complexes (containing as much as several hundred mg/l copper), with lesser zinc and silver cyanide complexes (present as weak cyanide complexes with as much as several tens of mg/l contained metals), and strong gold-cyanide complexes. Arsenic, cobalt, nickel, and iron may be present at low mg/l abundances in cyanide heap leach solutions. Thiocyanate (SCN-) abundances may be quite high in ore containing unoxidized sulfide minerals. At Summitville, degradation of cyanide accidentally released into the environment may have been enhanced by mixing with acid-mine drainage and the resulting breakdown of copper-cyanide complexes; thiocyanate likely did not degrade rapidly.

Smelter signatures

Epithermal quartz-alunite gold ore from which copper and silver were extracted during historic mining were probably smelted. No data have been identified concerning the mineralogy or chemical composition of soil affected by emissions from smelters that processed epithermal quartz-alunite gold ore. The closest analogue is Butte, Mont., where enargite-chalcocite-bornite ore from cordilleran lode deposits were smelted. There, soil proximal to smelters is very highly enriched in copper, arsenic, zinc, and lead.

Climate effects on environmental signatures

Currently available data are from moderately wet, seasonally temperate climate (Rocky Mountains). However, water draining advanced argillic ore in all climates is likely to be quite acidic and metal rich. Evaporation of acid drainage water, which leads to significant increases in metal concentrations and acidity, is important in all climates in which wet periods are interspersed with prolonged dry periods. At Summitville, evaporation has been an important process during dry Summer and Fall seasons even though total precipitation at the site exceeds 125 cm per year (Plumlee and others, 1995b). No data are available for tropical-humid, very dry, or arctic climates. Intense chemical weathering that affects exposed deposits in humid tropical climates oxidizes sulfide minerals to significant depths. Unless the area is simultaneously subjected to high rates of mechanical erosion, oxidation products isolate or reduce the underlying sulfide minerals, which inhibits continued oxidation; the potential for additional acid drainage generation is thereby limited.

Potential environmental effects

Potential downstream environmental effects of acid drainage in moderately wet to moderately dry climates can be significant in magnitude and spatial extent, especially if the surrounding geologic terrane is primarily composed of volcanic rocks with low acid buffering capacity. Predominant downstream signatures include elevated abundances of acid, iron, aluminum, manganese, and copper. Iron and aluminum form hydrous oxide precipitates as a result of dilution by downstream tributaries, and help sorb some of the dissolved metals. However, if water remains sufficiently acidic (due to limited dilution by downstream tributaries or acid generation resulting from precipitation of hydrous oxide minerals), manganese, copper, and zinc can persist (at abundances of hundreds $\mu\text{g/l}$, or more) in solution well downstream from mine sites (Smith and others, 1995).

In very wet climates, dilution may significantly reduce downstream effects. In dry or seasonally wet and dry climates, off-site drainage is greatest during short-term storm events or longer-term wet periods; reactions between this water and surrounding alkaline sediment (caliche) and soil, and with alkaline water draining the

sediment and soil, probably help mitigate acid drainage. Downstream storm water evaporation, however, may lead to the formation of acid- and metal-bearing salts that can themselves generate off-site acid drainage during storms (K. Stewart, unpub. data).

Guidelines for mitigation and remediation

- (1) Acid drainage can be successfully remediated using lime addition and sodium-bisulfide precipitation of metals (which produce acid-generating sludge). Lime addition to iron-rich drainage water may generate sufficient suspended particulates onto which a major fraction of dissolved arsenic, lead, and copper can sorb, thereby reducing or eliminating the need for sodium-bisulfide addition; in addition, wastes are non-acid-generating.
- (2) Isolation of unoxidized sulfide minerals and soluble secondary salts from oxidation and dissolution is crucial to acid drainage mitigation.
- (3) Surrounding carbonate-bearing rocks, including carbonate sedimentary rocks or carbonate-bearing propylitically altered rock on the fringes of deposits, should be carefully considered for their utility in acid-mine drainage mitigation. For example, acid water could be channelled through underground fracture systems in propylitic rock to help reduce acidity.
- (4) Cyanide heap-leach solutions should be treated by peroxide addition or other standard techniques. Heap-leach pads should be decommissioned by rinsing or bioremediation.
- (5) Mixing cyanide heap-leach solutions with acid drainage may effectively neutralize both. Acid in drainage water breaks down copper-cyanide complexes, forming volatile free cyanide and copper-iron-cyanide particulates, which degrade photolytically. Because of the alkalinity of heap-leach solutions, iron in acidic drainage precipitates as particulates, which then effectively sorb other metals contributed from acid drainage and heap-leach solutions.

Geoenvironmental geophysics

Resistivity studies can be used to identify rocks saturated with metal-bearing ground water. Porous rocks that can focus ground water flow can be identified by microgravity studies. Heat generated by sulfide mineral oxidation may have an associated thermal anomaly measurable by borehole logging or shallow probes; measures of excess heat flux can provide an approximation of total acid generation potential. Induced polarization methods can provide qualitative estimates of sulfide mineral percentages and grain size. The position, volume and mineralogy of clay bodies can be identified by induced polarization.

REFERENCES CITED

- Ashley, R.P., 1990, The Goldfield gold district, Esmeralda and Nye Counties, Nevada, *in* Shawe, D.R., Ashley, R.P., and Carter, L.M.H., eds., *Geology and resources of gold in the United States*: U.S. Geological Survey Bulletin 1857-H, p. H1-H7.
- Ball, J.W., and Nordstrom, D.K., 1989, Final revised analyses of major and trace elements from acid mine waters in the Leviathan Mine drainage basin, California and Nevada, October 1981 to October 1982: *Water-Resources Investigations*, Report No. WRI 89-4138, 46 p.
- Berger, B.R., 1986, Descriptive model of epithermal quartz-alunite Au, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 158.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Deen, J.A., Rye, R.O., Munoz, J.L., and Drexler, J.W., 1994, The magmatic hydrothermal system at Julcani, Peru: evidence from fluid inclusions and hydrogen and oxygen isotopes: *Economic Geology*, v. 89, p. 1924-1938.
- Gray, J.E., and Coolbaugh, M.F., 1994, Summitville, Colorado-Geologic framework and geochemistry of an epithermal acid-sulfate deposit formed in a volcanic dome: *Economic Geology*, v. 89, p. 1906-1923.
- Gray, J.E., Coolbaugh, M.F., Plumlee, G.S., and Atkinson, W.W., 1994, Environmental geology of the Summitville Mine, Colorado: *Economic Geology*, v. 89, p. 2006-2014.
- John, D.A., Nash, J.T., Clark, C.W., and Wulftange, W., 1991, Geology, hydrothermal alteration, and mineralization at the Paradise Peak gold-silver-mercury deposit, Nye County, Nevada, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., *Geology and ore deposits of the Great Basin*, Symposium proceedings: Reno, Geological Society of Nevada and U.S. Geological Survey, p. 1020-1050.
- Koyanagi, V.M., and Panteleyev, Andre, 1993, Natural acid-drainage in the Mount McIntosh/Pemberton Hills area, northern Vancouver Island (92L/12), *in* Grant, B., and others, eds.: *Geological fieldwork 1992; a summary of field activities and current research*, Ministry of Energy, Mines and Petroleum Resources, Report No. 1993-1, p. 445-450.

- Perkins, M., and Nieman, G.W., 1982, Epithermal gold mineralization in the South Mountain volcanic dome, Summitville, CO: Denver Region Exploration Geologists Symposium on the genesis of Rocky Mountain ore deposits: Changes with time and tectonics, Denver, Colorado, Nov. 4-5, 1982, Proceedings, p. 165-171.
- Plumlee, G.S., Gray, J.E., Roeber, M.M., Jr., Coolbaugh, M., Flohr, M., Whitney, G., 1995a, The importance of geology in understanding and remediating environmental problems at Summitville, *in* Posey, H.H., Pendleton, J.A., and Van Zyl, D., eds.: Proceedings, Summitville Forum '95, Colorado Geological Survey Special Publication #38, p. 13-22.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado-Implications for the prediction of mine-drainage chemistry: Proceedings, Mined Land Reclamation Symposium, Billings, Montana, p. 176-186.
- Plumlee, G.S., Smith, K.S., Mosier, E.L., Ficklin, W.H., Montour, M., Briggs, P.H., and Meier, A.L., 1995b,